Low-energy observables in a SUSY model with spontaneously broken R-Parity

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Theoretische Physik II

October 23, 2008

Outline

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What is Supersymmetry (SUSY)?

- connection between bosons and fermions
- no SUSY particle is observed yet $\Longrightarrow$ broken symmetry

Why do we think about SUSY?

- solution of the hierarchy problem
- dark matter candidates
- unification of gauge couplings at the GUT-scale
- electroweak symmetry breaking (EWSB) automatically
- explanation of neutrino masses

Minimal Supersymmetric Standard Model (MSSM): particle content

chiral supermultiplets	superfield-notation	spin-0-particles	spin-$\frac{1}{2}$-particles	quantum number of $SU(3)_C, SU(2)_L, U(1)_Y$
squarks, quarks	$\hat{Q}$	$(\tilde{u}_L, \tilde{d}_L)$	(u_L, d_L)	$(\mathbf{3}, \mathbf{2}, \frac{1}{6})$
($\times 3$ families)	$\hat{u}^c$	$\tilde{u}_R^*$	$u_R^\dagger$	$(\bar{\mathbf{3}}, \mathbf{1}, -\frac{2}{3})$
	$\hat{d}^c$	$\tilde{d}_R^*$	$d_R^\dagger$	$(\bar{\mathbf{3}}, \mathbf{1}, \frac{1}{3})$
sleptons, leptons	$\hat{L}$	$(\tilde{\nu}_e, \tilde{e}_L)$	(ν_e, e_L)	$(\mathbf{1}, \mathbf{2}, -\frac{1}{2})$
($\times 3$ families)	$\hat{e}^c$	$\tilde{e}_R^*$	$e_R^\dagger$	$(\mathbf{1}, \mathbf{1}, 1)$
Higgs, higgsinos	$\hat{H}_u$	(H_u^+, H_u^0)	$(\tilde{H}_u^+, \tilde{H}_u^0)$	$(\mathbf{1}, \mathbf{2}, \frac{1}{2})$
	$\hat{H}_d$	(H_d^0, H_d^-)	$(\tilde{H}_d^0, \tilde{H}_d^-)$	$(\mathbf{1}, \mathbf{2}, -\frac{1}{2})$

gauge supermultiplets	spin-$\frac{1}{2}$-particles	spin-1-particles	quantum number of $SU(3)_C, SU(2)_L, U(1)_Y$
gluinos, gluons	$\tilde{g}$	g	$(\mathbf{8}, \mathbf{1}, 0)$
winos, W-bosons	$\tilde{W}^\pm, \tilde{W}_3^0$	$W^\pm, W_3^0$	$(\mathbf{1}, \mathbf{3}, 0)$
bino, B-boson	$\tilde{B}$	B	$(\mathbf{1}, \mathbf{1}, 0)$

Basic object to build the Lagrangian is the so-called Superpotential:

$$\mathcal{W}_{\text{MSSM}} = \epsilon_{ab}\left[h_u^{ij}\hat{Q}_i^a\hat{u}_j^c\hat{H}_u^b + h_d^{ij}\hat{Q}_i^b\hat{d}_j^c\hat{H}_d^a + h_e^{ij}\hat{L}_i^b\hat{e}_j^c\hat{H}_d^a - \hat{\mu}\hat{H}_d^a\hat{H}_u^b\right]$$

$\hat{\mu}$ has to be of the order of the electroweak scale $\mathcal{O}(m_t)$
$\Longrightarrow$ $\hat{\mu}$-problem

Sfermion-fermion-gaugino interaction enter the Lagrangian through

$$-\sqrt{2}g\left(\phi^* T^a \psi\right)\lambda^a - \sqrt{2}g\lambda^{\dagger a}\left(\psi^\dagger T^a \phi\right)$$

Rotating the MSSM-Lagrangian from gauge into mass eigenbasis yields to the following mass spectra of SUSY-particles:

- squarks and sleptons are mixing in pairs
- four charginos $\chi_1^\pm$, $\chi_2^\pm$ as result of the mixing between $\tilde{W}^\pm$, $\tilde{H}_u^+$ and $\tilde{H}_d^-$
- the neutral fermions $\tilde{W}^0$, $\tilde{B}$, $\tilde{H}_u^0$ and $\tilde{H}_d^0$ form the four neutralinos $\chi_1^0, \ldots, \chi_4^0$

Why do neutrinos not mix with neutralinos in the case of the MSSM?
$\Longrightarrow$ R-Parity is conserved!

What is R-Parity?

R-Parity is a Z_2-symmetry.

$$P_{\mathsf{R}} = (-1)^{3(B-L)+2s}$$

B indicates the baryon number, L the lepton number and s the spin.

$\Longrightarrow P = 1$ for SM particles $\Longrightarrow P = -1$ for SUSY particles

Conserved R-Parity forbids the terms

$$\mathcal{W}_{\not R} = \underbrace{\epsilon_{ab}\left(\tfrac{1}{2}\lambda_{ijk}\hat{L}_i^a\hat{L}_j^b\hat{e}_k^c + \lambda'_{ijk}\hat{L}_i^a\hat{Q}_j^b\hat{d}_k^c - \varepsilon_i\hat{L}_i^a\hat{H}_u^b\right)}_{\Delta L=1} + \underbrace{\tfrac{1}{2}\lambda''_{ijk}\hat{u}_i^c\hat{d}_j^c\hat{d}_k^c}_{\Delta B=1}$$

Why should R-Parity be ...

... conserved?

- combined lepton ($\not{L}$) and baryon number violation ($\not{B}$) give rise to proton decay channels, e.g. $p \to \pi^0 e / \pi^+ \nu$
- no contributions to flavour-changing-neutral-currents (FCNC) and lepton-flavour-violation (LFV) on tree-level
- lightest SUSY particale cannot decay $\Longrightarrow$ dark matter candidate

... broken?

- neutrino-neutralino-mixing $\Longrightarrow$ neutrino masses

Outline

The superpotential reads

$$\mathcal{W} = \epsilon_{ab}\Big[h_u^{ij}\hat{Q}_i^a\hat{u}_j^c\hat{H}_u^b + h_d^{ij}\hat{Q}_i^b\hat{d}_j^c\hat{H}_d^a + h_e^{ij}\hat{L}_i^b\hat{e}_j^c\hat{H}_d^a + h_\nu^{ij}\hat{L}_i^a\hat{\nu}_j^c\hat{H}_u^b - h_0\hat{H}_d^a\hat{H}_u^b\hat{\Phi}\Big] + \frac{\lambda}{3!}\hat{\Phi}^3 + h^{ij}\hat{\Phi}\hat{\nu}_i^c\hat{S}_j$$

A. Masiero and J. W. F. Valle, Phys. Lett. B251, 273-278 (1990)

with additional singlet superfields $\hat{\Phi}$, $\hat{S}_i$ and $\hat{\nu}_i^c$ possesing lepton numbers $(0, 1, -1)$. The terms can be identified as:

- known MSSM superpotential terms
- solution of the $\hat{\mu}$-problem by an effective $\mu = h_0\frac{v_\Phi}{\sqrt{2}}$ since the scalar component of $\hat{\Phi}$ acquires a VEV (as in NMSSM)
- spontaneously R-Parity violating (SRPV) terms

Advantages and effects:

- $\not{L}$ as a result of EWSB
- the VEVs $\langle\tilde{\nu}^c\rangle = \frac{v_R}{\sqrt{2}}$, $\langle\tilde{S}\rangle = \frac{v_S}{\sqrt{2}}$ and $\langle\tilde{\nu}_{Li}\rangle = \frac{v_{Li}}{\sqrt{2}}$ drive **only** $\not{L}$
  $\Longrightarrow$ no problems with proton decay
- $\hat{\mu}$-problem is solved by the effective parameter $\mu = h_0 \frac{v_\Phi}{\sqrt{2}}$
- Due to the broken global symmetry a massless, CP-odd Nambu-Goldstone boson called Majoron arises.
- Neutrino masses are generated at tree level.

In the gauge eigenbasis

$$\left(\psi^0\right)^T = \left(\ \tilde{B}^0,\quad \tilde{W}_3^0,\quad \tilde{H}_d^0,\quad \tilde{H}_u^0,\quad \nu^c,\quad S,\quad \Phi,\quad \nu_i\ \right)$$

the neutralino mass matrix occurring in $\mathcal{L}^{\text{mass}}_{\text{neutral}} = -\frac{1}{2}\left(\psi^0\right)^T M_N \psi^0 + h.c.$ reads

$$M_N = \begin{pmatrix} M_{\chi^0} & m_{\chi^0\nu^c} & 0 & m_{\chi^0\Phi} & m_{\chi^0\nu} \\ m^T_{\chi^0\nu^c} & 0 & h\frac{v_\Phi}{\sqrt{2}} & h\frac{v_S}{\sqrt{2}} & m_D^T \\ 0 & h\frac{v_\Phi}{\sqrt{2}} & 0 & h\frac{v_R}{\sqrt{2}} & 0 \\ m^T_{\chi^0\Phi} & h\frac{v_S}{\sqrt{2}} & h\frac{v_R}{\sqrt{2}} & \lambda\frac{v_\Phi}{\sqrt{2}} & 0 \\ m^T_{\chi^0\nu} & m_D & 0 & 0 & 0 \end{pmatrix}$$

containing the Dirac mass matrix $(m_D)_i = \frac{1}{\sqrt{2}} h_\nu^i v_u$ and the R-Parity violating matrix $\left(m^T_{\chi^0\nu}\right)_i = \left(-\frac{1}{2}g' v_{Li},\ \frac{1}{2} g v_{Li},\ 0,\ h_\nu^i \frac{v_R}{\sqrt{2}}\right)_i$

Seesaw-like diagonalization of the neutralino mass matrix leads to the effective neutrino mass matrix

$$m_{\nu\nu}^{\text{eff}} = -M_D^T \cdot M_H^{-1} \cdot M_D,$$

Finally one can find the approximation

$$-\left(m_{\nu\nu}^{\text{eff}}\right)_{ij} = a\Lambda_i\Lambda_j + b\left(\epsilon_i\Lambda_j + \epsilon_j\Lambda_i\right) + c\epsilon_i\epsilon_j.$$

including the parameters

$$\mathbf{\Lambda_i = \epsilon_i v_d + \mu v_{Li}} \quad \text{and} \quad \mathbf{\epsilon_i = h_\nu^i \frac{v_R}{\sqrt{2}}}.$$

These two vectors are sufficient to control neutrino physics!

Considering **only** $\vec{\Lambda}$ yields:

$$V^{(\nu)} = \begin{pmatrix} \frac{\sqrt{\Lambda_2^2+\Lambda_3^2}}{|\vec{\Lambda}|} & 0 & \frac{\Lambda_1}{|\vec{\Lambda}|} \\ -\frac{\Lambda_1\Lambda_2}{\sqrt{\Lambda_2^2+\Lambda_3^2}|\vec{\Lambda}|} & \frac{\Lambda_3}{\sqrt{\Lambda_2^2+\Lambda_3^2}} & \frac{\Lambda_2}{|\vec{\Lambda}|} \\ -\frac{\Lambda_1\Lambda_3}{\sqrt{\Lambda_2^2+\Lambda_3^2}|\vec{\Lambda}|} & -\frac{\Lambda_2}{\sqrt{\Lambda_2^2+\Lambda_3^2}} & \frac{\Lambda_3}{|\vec{\Lambda}|} \end{pmatrix}$$

$\Longrightarrow$ two angles for direct reading

$$\tan^2\theta_{\mathrm{R}} \approx \left(\frac{\Lambda_1}{\sqrt{\Lambda_2^2+\Lambda_3^2}}\right)^2 \quad \text{and} \quad \tan^2\theta_{\mathrm{atm}} \approx \left(\frac{\Lambda_2}{\Lambda_3}\right)^2$$

Generation of third angle requires $\vec{\tilde{\epsilon}} = \left(V^{(\nu)}\right)^T \cdot \vec{\epsilon}$:

$$\tan^2\theta_{\mathrm{sol}} \approx \left(\frac{\tilde{\epsilon}_1}{\tilde{\epsilon}_2}\right)^2$$

Current neutrino oscillation data containing mixing angles and the mass differences $\Delta m_{ij}^2 = m_i^2 - m_j^2$:

parameter	best fit (1σ)	2σ	3σ
Δm_{21}^2 $\left[10^{-5}\text{ eV}^2\right]$	$7.65^{+0.23}_{-0.20}$	$7.25 - 8.11$	$7.05 - 8.34$
Δm_{31}^2 $\left[10^{-2}\text{ eV}^2\right]$	$2.40^{+0.12}_{-0.11}$	$2.18 - 2.64$	$2.07 - 2.75$
$\sin^2\theta_{12}$	$0.304^{+0.022}_{-0.016}$	$0.27 - 0.35$	$0.25 - 0.37$
$\sin^2\theta_{23}$	$0.50^{+0.07}_{-0.06}$	$0.39 - 0.63$	$0.36 - 0.67$
$\sin^2\theta_{13}$	$0.01^{+0.016}_{-0.011}$	≤ 0.040	≤ 0.056

T. Schwetz, M. Tortola and J. W. F. Valle, arXiv:0808.2016 (2008)

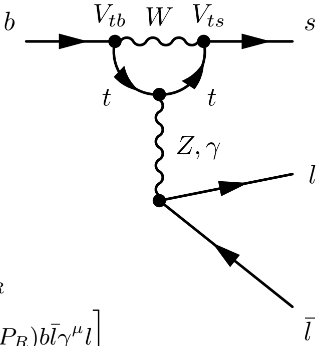
All allowed values can be reached by variing $\vec{\Lambda}$ and $\vec{\epsilon}$ respectively the $\not{R}$ parameters.

Outline

Approach and Motivation

- fitting the $\not{R}$ parameters to neutrino data
- searching pocesses which are giving additional constraints (e.g. loop suppressed or forbidden processes)

$B \rightarrow X_S ll$ in SM



- loop suppressed
- matrix element:

$$
\begin{aligned}
\mathcal{M}_{\text{SM}} = & \frac{G_F \alpha}{\sqrt{2}\pi} V_{ts}^* V_{tb} \cdot \\
& \Big[(C_9^{\text{eff}} - C_{10}) \bar{s}_L \gamma_\mu b_L \bar{l}_L \gamma^\mu l_L \\
& + (C_9^{\text{eff}} + C_{10}) \bar{s}_L \gamma_\mu b_L \bar{l}_R \gamma^\mu l_R \\
& - 2 C_7^{\text{eff}} \bar{s} i \sigma_{\mu\nu} \frac{q^\nu}{q^2} (m_s P_L + m_b P_R) b \bar{l} \gamma^\mu l \Big]
\end{aligned}
$$

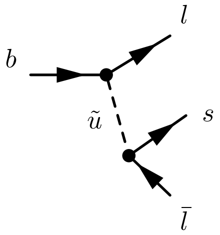
- experimental value:

$$\mathcal{B}\left(B \rightarrow X_s l^+ l^-\right) = (1.60 \pm 0.51) \cdot 10^{-6}$$

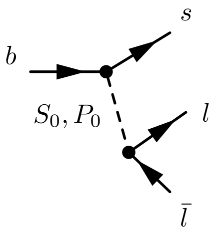
T. Huber et al., Nucl. Phys. B740, 105-137 (2006)

$B \to X_S ll$ in SRPV Model

- treelevel process suppressed by $\not{R}$ parameters



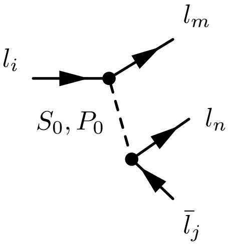
- additional contributions:

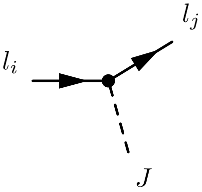


$$\mathcal{M}_{\text{add}} = \frac{g^2}{2m_{\tilde{u}_L}^2} \Big(C_{LR}(\bar{l}_L \gamma^\mu l_L \bar{s}_R \gamma_\mu b_R) + C_{RL}(\bar{l}_R \gamma^\mu l_R \bar{s}_L \gamma_\mu b_L) + C_{LRLR}(\bar{l}_L l_R \bar{s}_L b_R) + C_{RLRL}(\bar{l}_R l_L \bar{s}_R b_L) + C_{RLLR}(\bar{l}_R l_L \bar{s}_L b_R) + C_{LRRL}(\bar{l}_L l_R \bar{s}_R b_L) + \frac{C_T}{8}(\bar{l}\sigma^{\mu\nu} l \bar{s}\sigma_{\mu\nu} b) + i\frac{C_{TE}}{16}(\bar{l}\sigma_{\mu\nu} l \bar{s}\sigma_{\alpha\beta} b)\epsilon^{\mu\nu\alpha\beta} \Big)$$

Leptonic decays

- violated lepton flavour conservation (LFC)
- not predicted by the SM or MSSM on tree-level





Two mSUGRA scenarios:

SPS1a:

parameter	value in GeV
$m_{1/2}$	250
m_0	100
A_0	-100

parameter	value
sign(μ)	$+1$
$\tan\beta$	10

SPS4:

parameter	value in GeV
$m_{1/2}$	300
m_0	400
A_0	0

parameter	value
sign(μ)	$+1$
$\tan\beta$	50

RGEs of the MSSM are used to get the corresponding MSSM parameters at electroweak scale.

$\not{R}$ violating parameters:

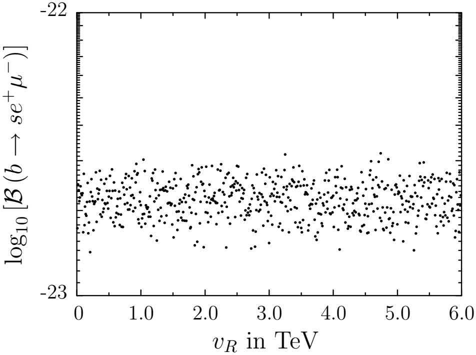
- determined by neutrino fit routine:

$$\Lambda_i = \epsilon_i v_d + \mu v_{Li} \quad \text{and} \quad \epsilon_i = h_\nu^i \frac{v_R}{\sqrt{2}}$$

- fixed by the effective parameter μ

$$\mu = h_0 \frac{v_\Phi}{\sqrt{2}}$$

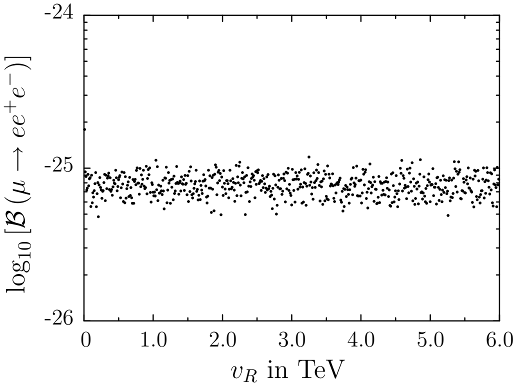
- all variations show only very poor dependences
- $\mathcal{B}(b \to s l_i^+ l_i^-)$: almost constant at $1.92 \cdot 10^{-6}$
- $\mathcal{B}(b \to s l_i^+ l_j^-)$: unmeasurable small



SPS1a: $\vec{\Lambda} \to \theta_{\text{atm}}$, variation of $v_R = v_S$

$\Longrightarrow$ no additional constraints to $\not{R}$ parameters

Leptonic threebody decays



SPS4: $\vec{\Lambda} \to \theta_{\text{atm}}$, variation of $v_R = v_S$

All variations show only very poor dependencies on $R\!\!\!/$ parameters and are much below experimental bounds if measurable at all.

maximal magnitude of the branching ratios:

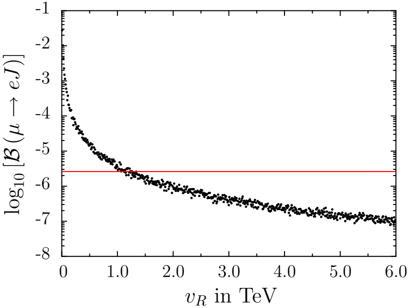
branching ratio	SPS$1a$		SPS4		experimental upper bound
	$\theta_{\text{atm}} \to \vec{\Lambda}$	$\theta_{\text{atm}} \to \vec{\epsilon}$	$\theta_{\text{atm}} \to \vec{\Lambda}$	$\theta_{\text{atm}} \to \vec{\epsilon}$	
$\mathcal{B}\left(\mu \to e e^+ e^-\right)$	$\mathcal{O}(10^{-26})$	$\mathcal{O}(10^{-27})$	$\mathcal{O}(10^{-25})$	$\mathcal{O}(10^{-23})$	$1.0 \cdot 10^{-12}$
$\mathcal{B}\left(\tau^- \to e^- e^+ e^-\right)$	$\mathcal{O}(10^{-24})$	$\mathcal{O}(10^{-25})$	$\mathcal{O}(10^{-24})$	$\mathcal{O}(10^{-21})$	$2.0 \cdot 10^{-7}$
$\mathcal{B}\left(\tau^- \to e^- \mu^+ e^-\right)$	$\mathcal{O}(10^{-24})$	$\mathcal{O}(10^{-32})$	$\mathcal{O}(10^{-24})$	$\mathcal{O}(10^{-21})$	$1.1 \cdot 10^{-7}$
$\mathcal{B}\left(\tau^- \to e^- \mu^- e^+\right)$	$\mathcal{O}(10^{-23})$	$\mathcal{O}(10^{-24})$	$\mathcal{O}(10^{-23})$	$\mathcal{O}(10^{-20})$	$2.7 \cdot 10^{-7}$
$\mathcal{B}\left(\tau^- \to e^- \mu^+ \mu^-\right)$	$\mathcal{O}(10^{-20})$	$\mathcal{O}(10^{-21})$	$\mathcal{O}(10^{-19})$	$\mathcal{O}(10^{-16})$	$3.3 \cdot 10^{-7}$
$\mathcal{B}\left(\tau^- \to \mu^- e^+ \mu^-\right)$	$\mathcal{O}(10^{-23})$	$\mathcal{O}(10^{-24})$	$\mathcal{O}(10^{-23})$	$\mathcal{O}(10^{-20})$	$1.3 \cdot 10^{-7}$
$\mathcal{B}\left(\tau^- \to \mu^- \mu^+ \mu^-\right)$	$\mathcal{O}(10^{-19})$	$\mathcal{O}(10^{-20})$	$\mathcal{O}(10^{-19})$	$\mathcal{O}(10^{-16})$	$1.9 \cdot 10^{-7}$

U. Bellgardt et al., Nucl. Phys. B299, 1 (1988)

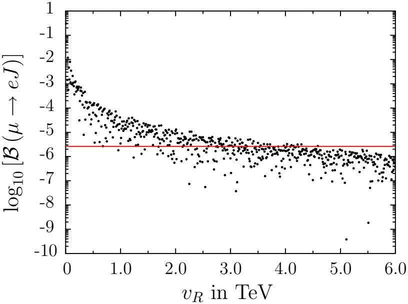
B. Aubert et al., Phys. Rev. Lett. 92, 121801 (2004)

$\Longrightarrow$ no additional constraints to $\not{R}$ parameters

Leptonic decay $\mu \to eJ$



SPS1: $\vec{\Lambda} \to \theta_{\text{atm}}$, variation of $v_R = v_S$



SPS1: $\vec{\epsilon} \to \theta_{\text{atm}}$, variation of $v_R = v_S$

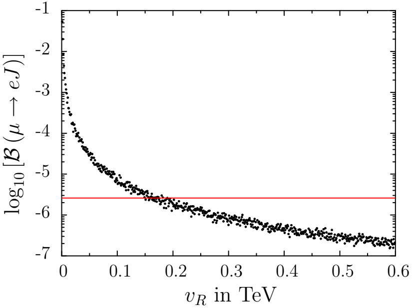
experimental bound $2.6 \cdot 10^{-6}$ (TRIUMF)

$\Longrightarrow v_R$ must be at least about 1 TeV

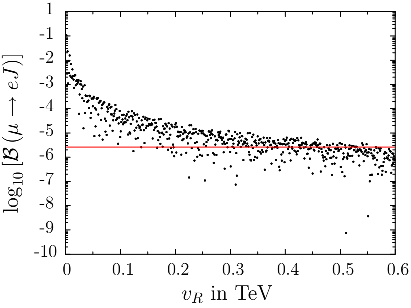
J. C. Romão et al., Nucl. Phys. B363, 369-384 (1991)

A. Jodidio et al., Phys. Rev. D34, 1967-1990 (1986)

Leptonic decay $\mu \to eJ$



SPS1: $\vec{\Lambda} \to \theta_{\text{atm}}$, variation of $v_R = 0.1 \cdot v_S$

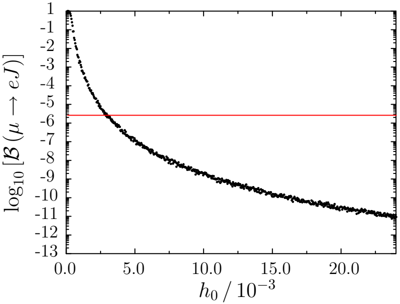


SPS1: $\vec{\epsilon} \to \theta_{\text{atm}}$, variation of $v_R = 0.1 \cdot v_S$

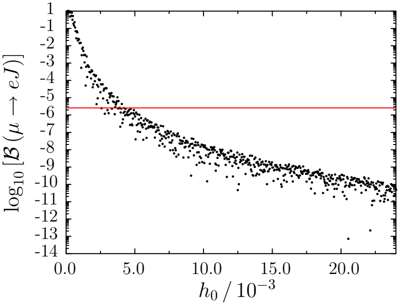
experimental bound $2.6 \cdot 10^{-6}$ (TRIUMF)

$\Longrightarrow v_R$ must be at least about 100 GeV

Leptonic decay $\mu \to eJ$

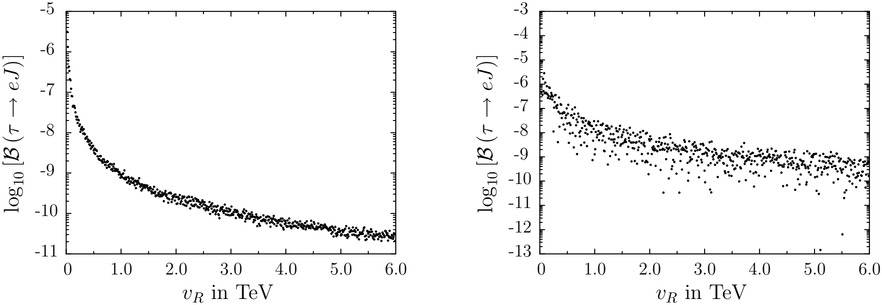


SPS1: $\vec{\Lambda} \to \theta_{\text{atm}}$, variation of h_0 by $v_R = 1$ TeV



SPS1: $\vec{\epsilon} \to \theta_{\text{atm}}$, variation of h_0 by $v_R = 1$ TeV

Leptonic decay $\tau \to eJ$



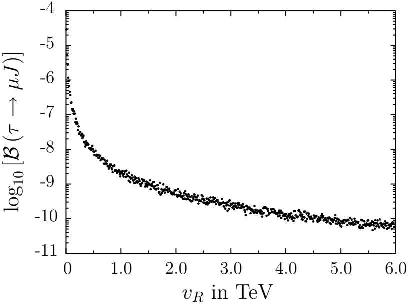
SPS1: $\vec{\Lambda} \to \theta_{\text{atm}}$, variation of $v_R = v_S$ SPS1: $\vec{\epsilon} \to \theta_{\text{atm}}$, variation of $v_R = v_S$

experimental bound $7.12 \cdot 10^{-3}$ (MARK-III)

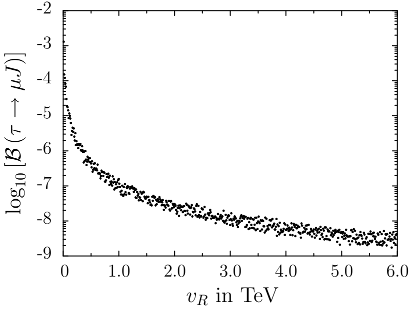
$\Longrightarrow$ no additional constraints

J. C. Romão et al., Nucl. Phys. B363, 369-384 (1991)
R. M. Baltrusaitis et al., Phys. Rev. Lett. 55, 1842-1845 (1985)

Leptonic decay $\tau \to \mu J$



SPS1: $\vec{\Lambda} \to \theta_{\text{atm}}$, variation of $v_R = v_S$



SPS1: $\vec{\epsilon} \to \theta_{\text{atm}}$, variation of $v_R = v_S$

experimental bound $2.25 \cdot 10^{-2}$ (MARK-III)

$\Longrightarrow$ no additional constraints

J. C. Romão et al., Nucl. Phys. B363, 369-384 (1991)

R. M. Baltrusaitis et al., Phys. Rev. Lett. 55, 1842-1845 (1985)

Outline

Conclusions

- $B \rightarrow X_s ll$ and leptonic threebody decays obtain no additional constraints to $\not{R}$ parameters once neutrino physics are fulfilled
- $\mu \rightarrow eJ$ constricts the parameter space
- $\tau \rightarrow lJ$ yield no crucial bounds yet